The Environmental Sample Processor: Running an Underwater Laboratory on a Fixed Energy Budget

Brent Roman

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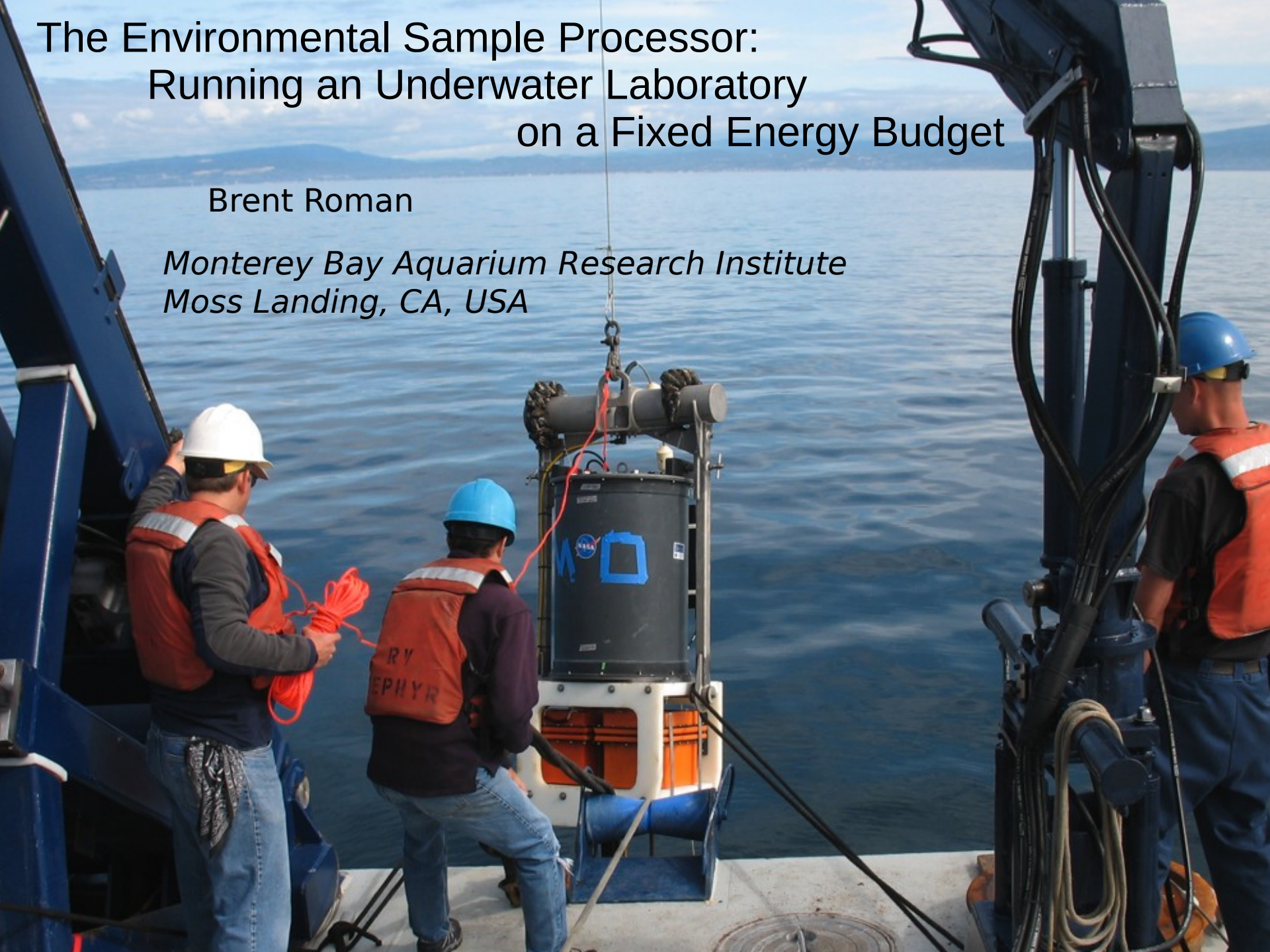
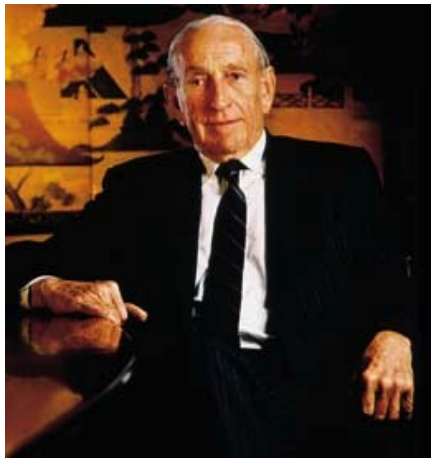
Moss Landing, CA, USA



The Monterey Bay Aquarium and MBARI

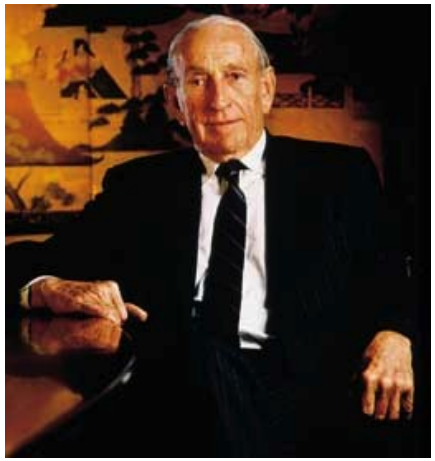


David Packard (1912-1996)

Monterey Bay Aquarium

The Monterey Bay Aquarium and MBARI

HEWLETT® PACKARD



David Packard (1912-1996)

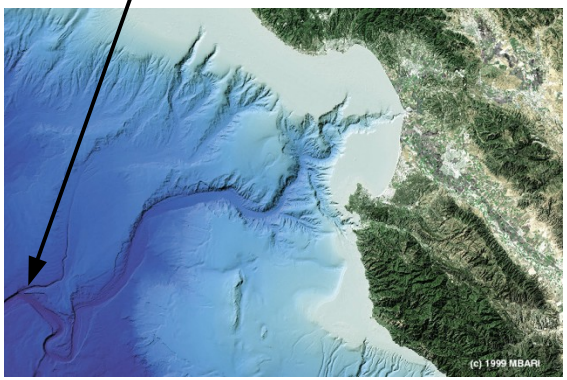
Monterey Bay Aquarium
Research Institute (MBARI)

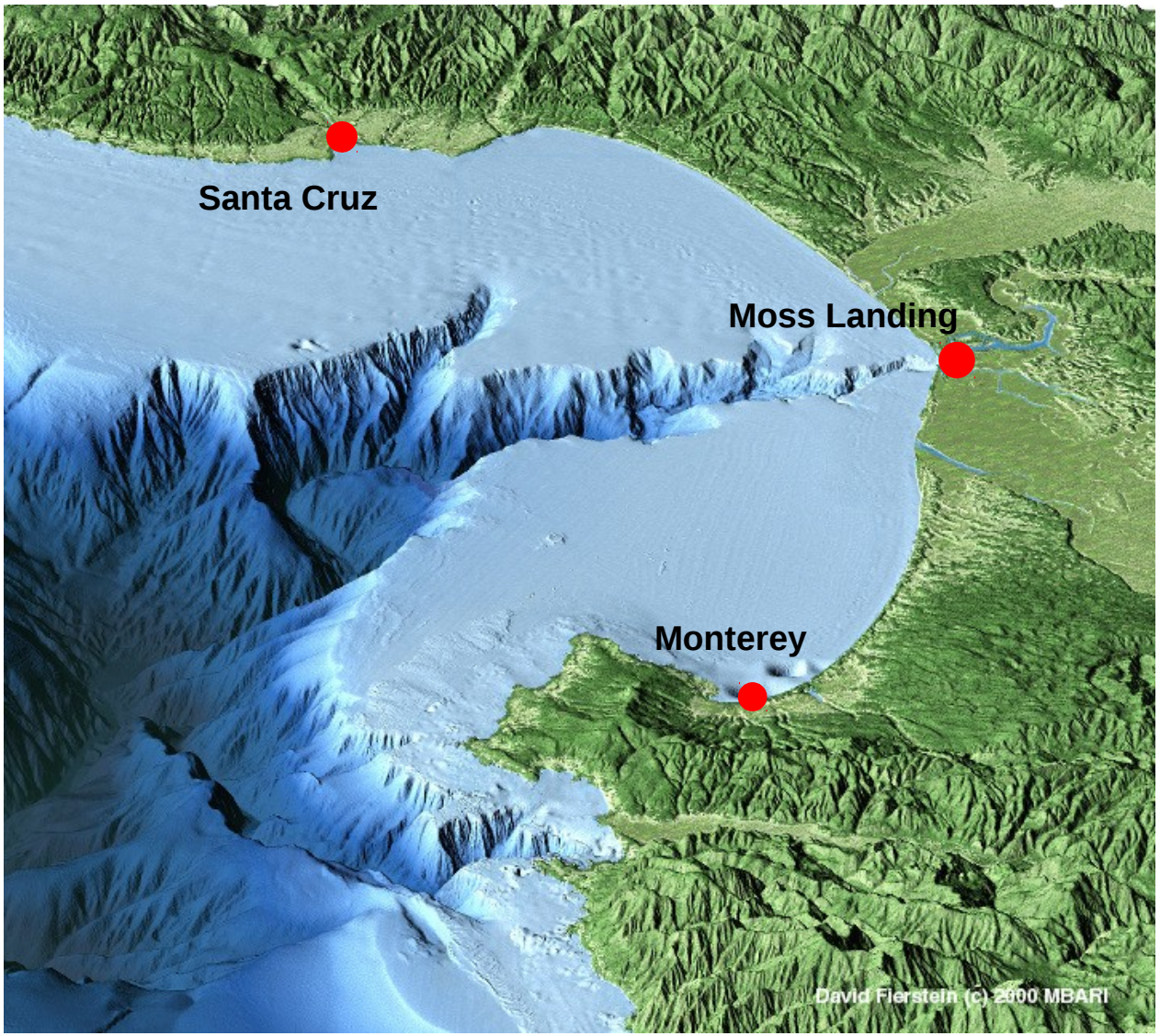
Not for profit
$45M/yr annual budget
220 people
1/3 Science, 1/3 Engineering, 1/3 Admin

Monterey Bay

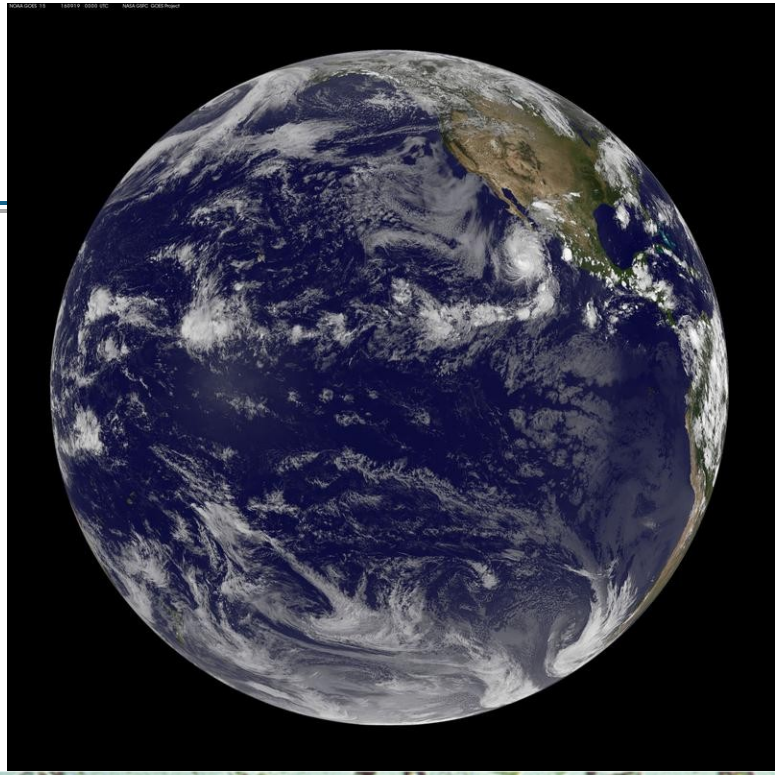
Why Moss Landing?

- Monterey Bay Submarine Canyon within 1-day steam
- Canyon is ~2000 meters deep, comparable to Grand Canyon
- Monterey Canyon Fan is ~3600 meters deep





The Microbial Ocean



71% of the earth's surface
➔ is covered with water
(96% of which is in oceans)

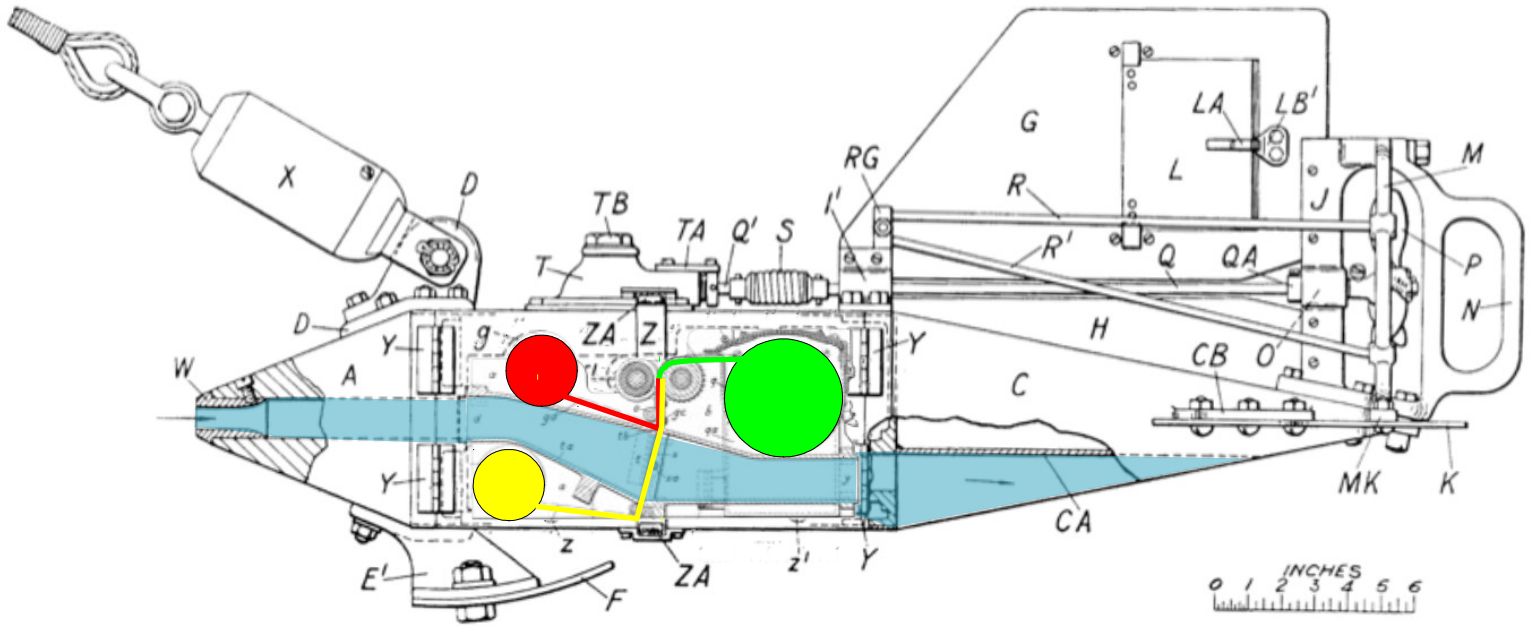
Where there is water and light:
➔ *there are plankton!*

Plankton:
+ Produce >50% of our oxygen
+ Form base of ocean's food web
+ Regulate CO_2 in our air
- Release greenhouse gases
- Secrete neurotoxins

Harmful Algal Blooms (Red Tides)

- Poison accumulates in shellfish
- Kills fish, birds and mammals
- Closes fisheries and beaches
- Traditional detection takes days
- *Not all Red Tides are Harmful*

Automated Filtering is a surprisingly Old Idea

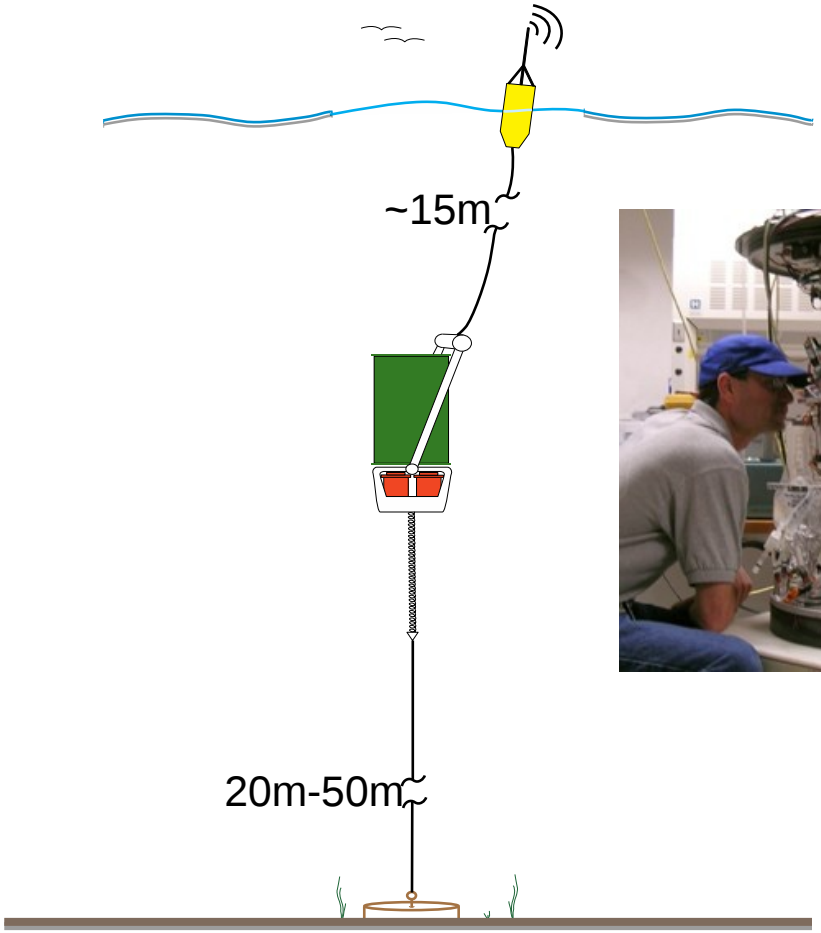


Continuous Plankton Recorder (CPR)

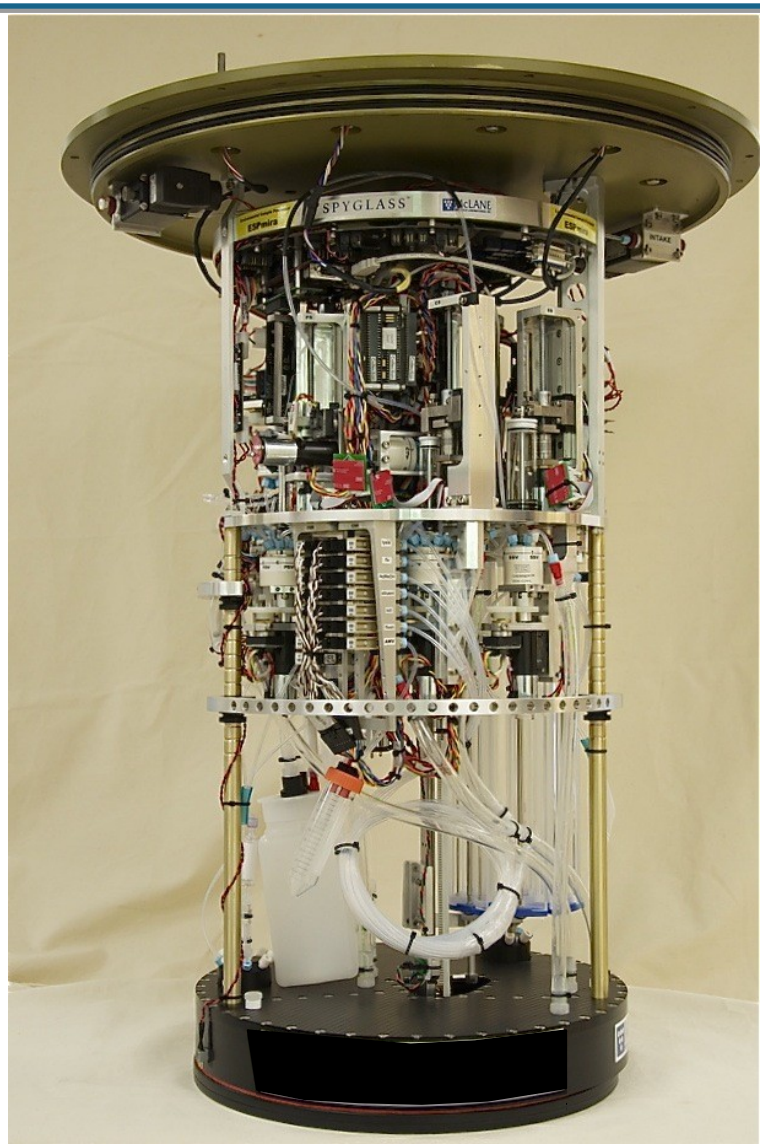
- First deployed on the R.R.S. Discovery in 1925-27.
- Towed behind ship, prop drives scrolling gauze filter
- Designed to document plankton “patchiness”
- Took ~10 yrs to become “operational”, still in use!
- Mechanically powered

Environmental Sample Processor (ESP)

“Lab-in-a-can”



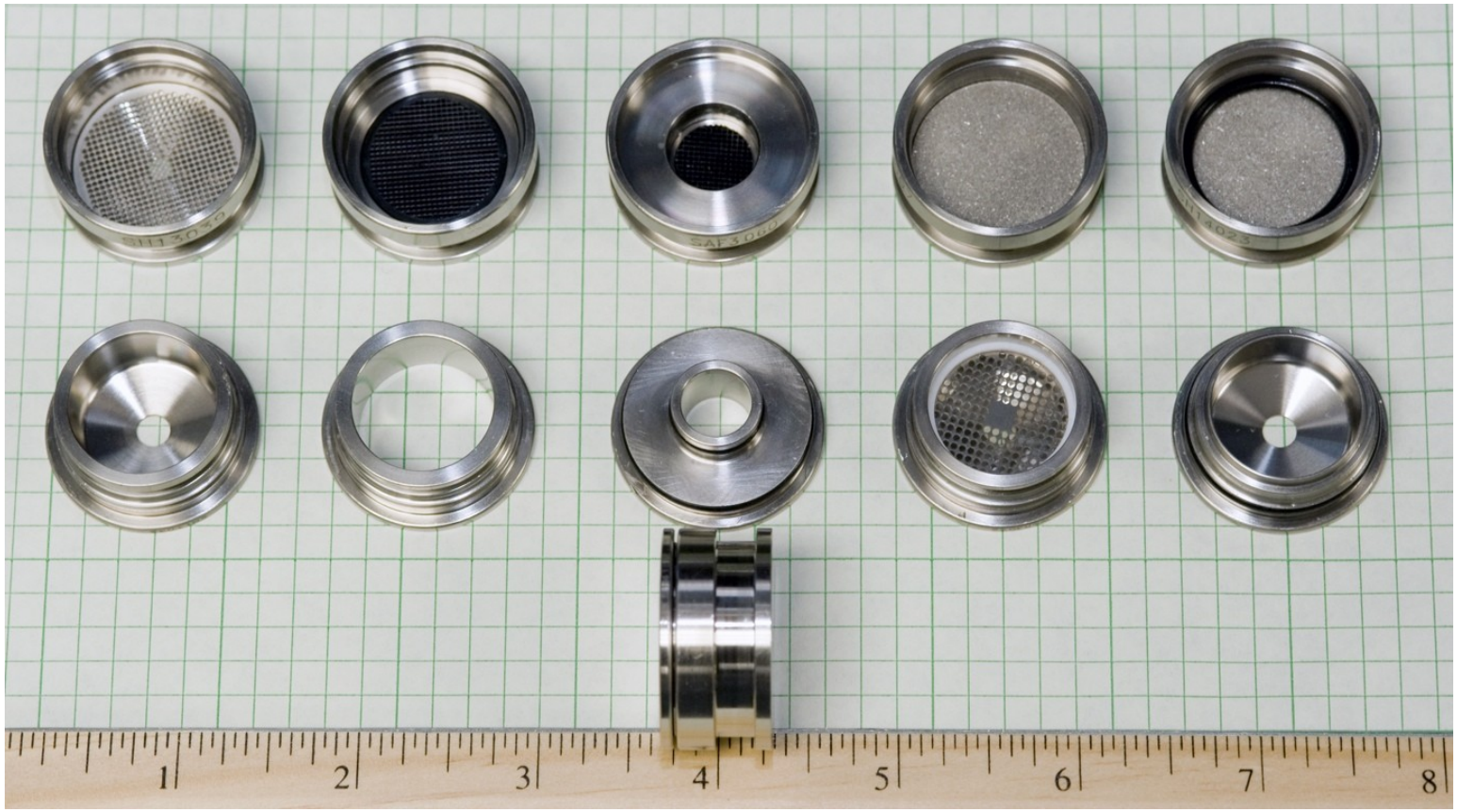
Positioned 5 – 15m under surface
Battery powered



Development begun 1996

Pucks Replace Scrolling Filter

Function as filter holders and reaction vessels



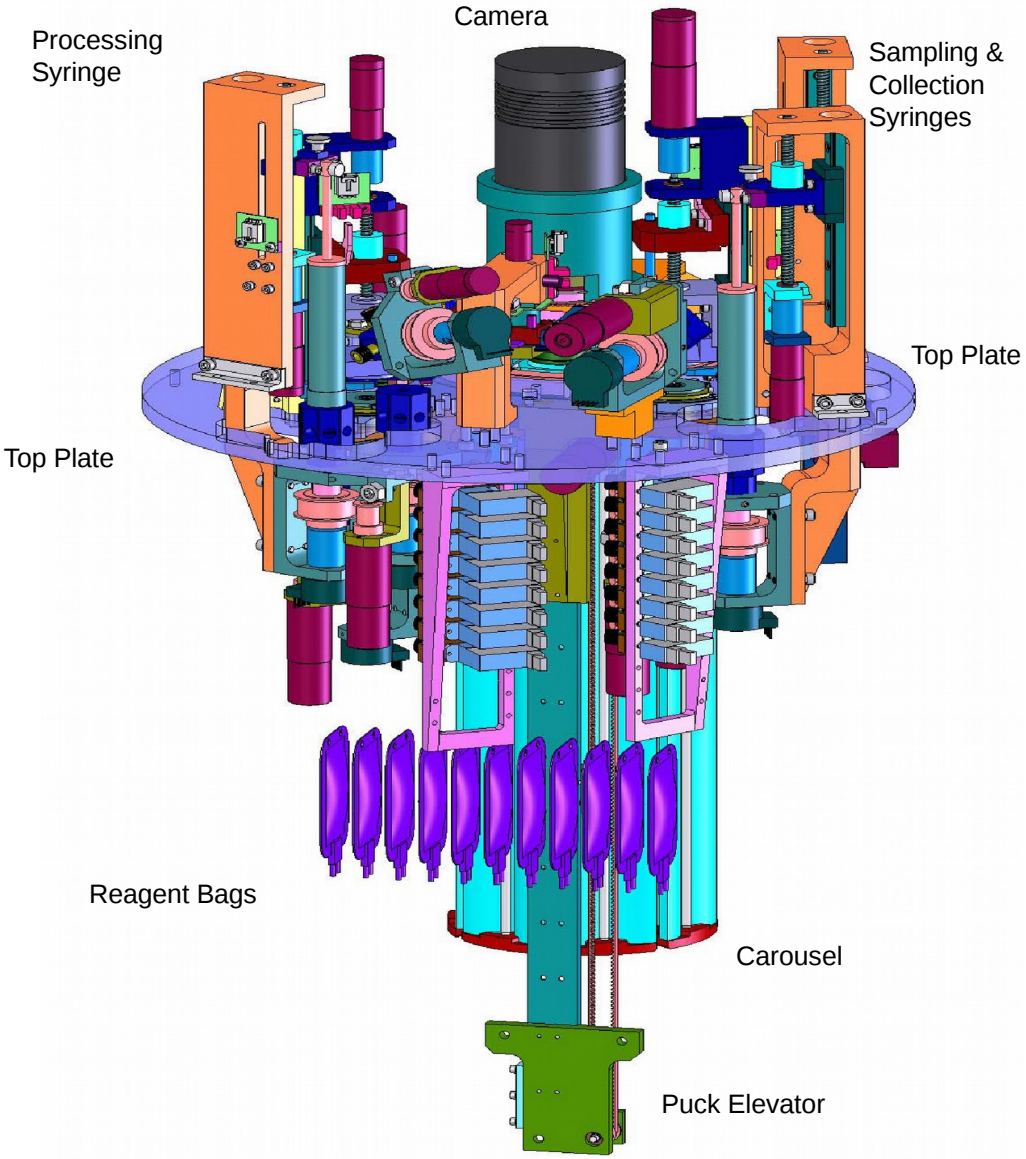
- Raw water collection
- Sample preservation
- Real-Time Array Imaging

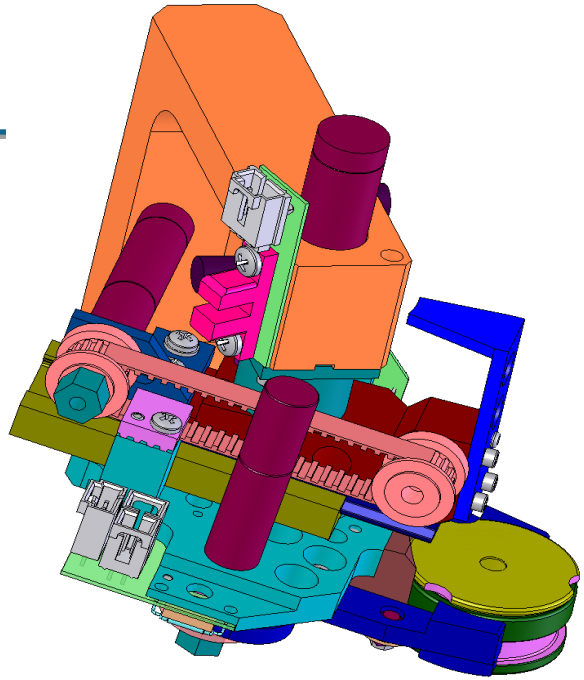
1 inch = 2.54cm

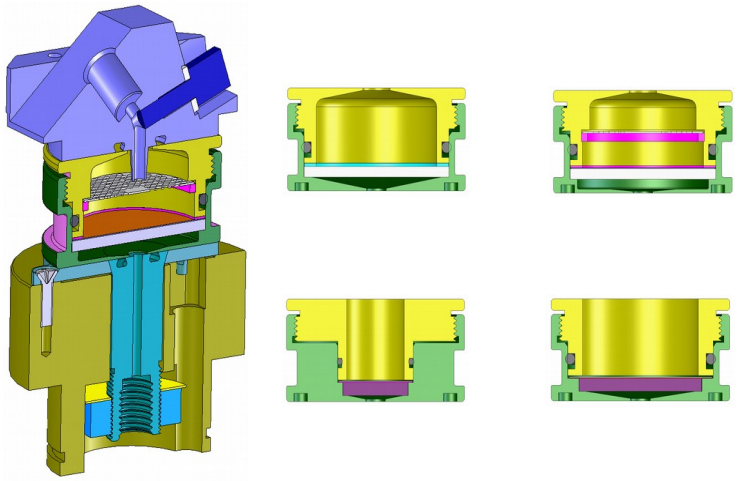
Top & Bottom halves snap together with rubber O-ring seals


Environmental Sample
Processor
(ESP)

ESP Core robotics

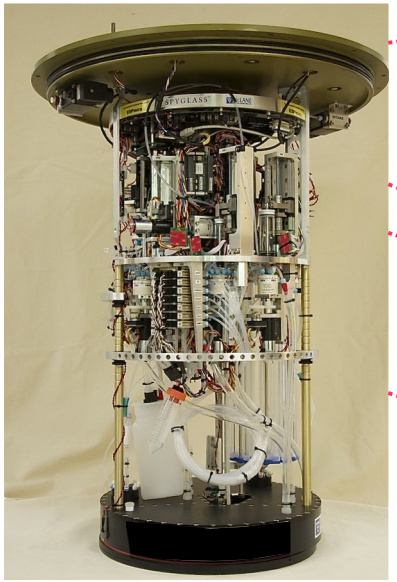




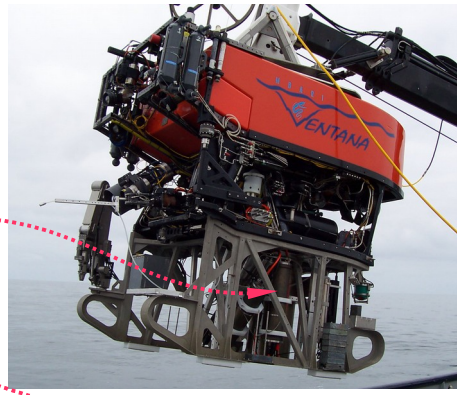


Deployment Platforms

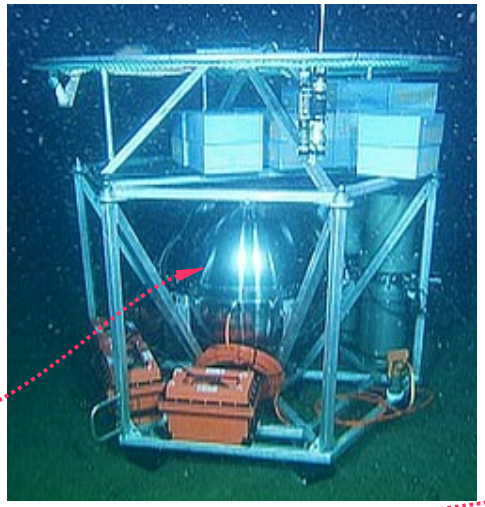
ESP Core



ROV tool sled



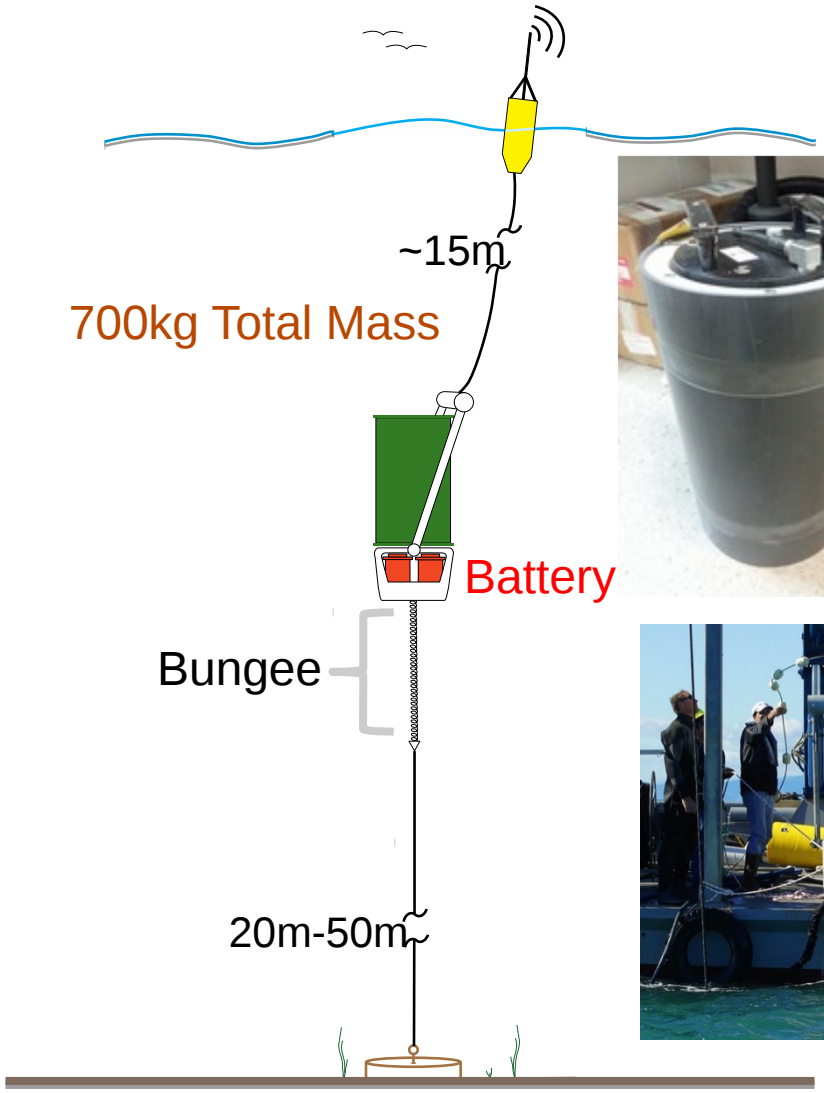
Ocean Bottom

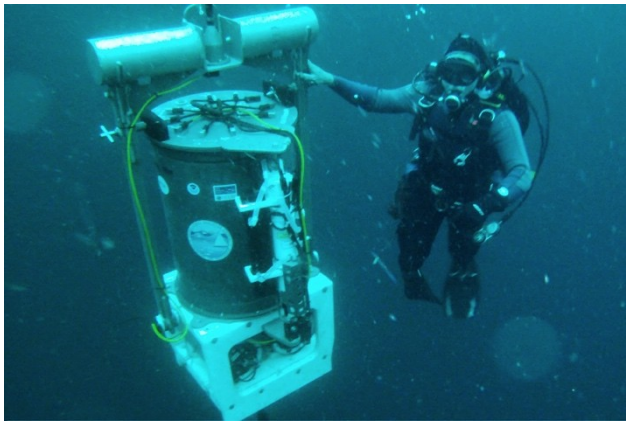


Surface Drifter

Pier

Shallow Moored Deployments





Power Management is Key
to achieve 6 month deployments

360 Alkaline 'D' Cells

Lead-acid used initially – but only stored 2kWh

\+ ***Alkaline is as energy dense as Li-Ion, but much safer***

\+ Very inexpensive

\- Not rechargable

76kg including waterproof housings

Minimizing “Active” Power Consumption

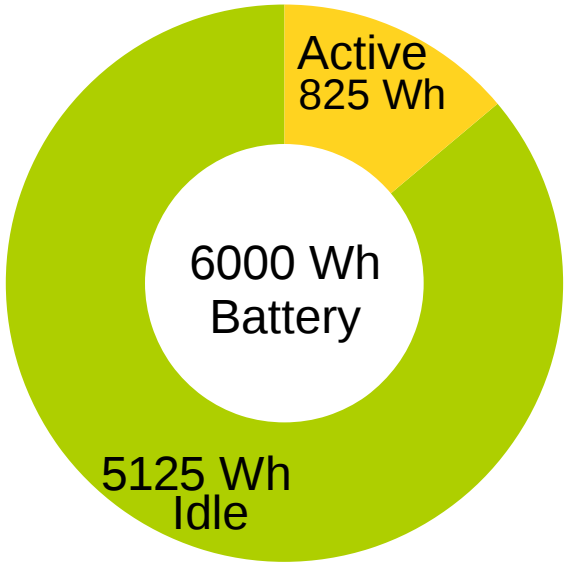
- Custom Low Power DC Servo Microcontrollers
  - Designed in 2002 – Quiescent draw = ~70mW
- Multi-Master I^2C bus
  - Lower power than CAN or RS-485
  - Makes adding controllers easy
  - Eliminates polling
- TI MSP430F169 consumes < 1mW
  - But provides only 2kBytes RAM
  - I^2C silicon bugs cost 4 man months

In retrospect...

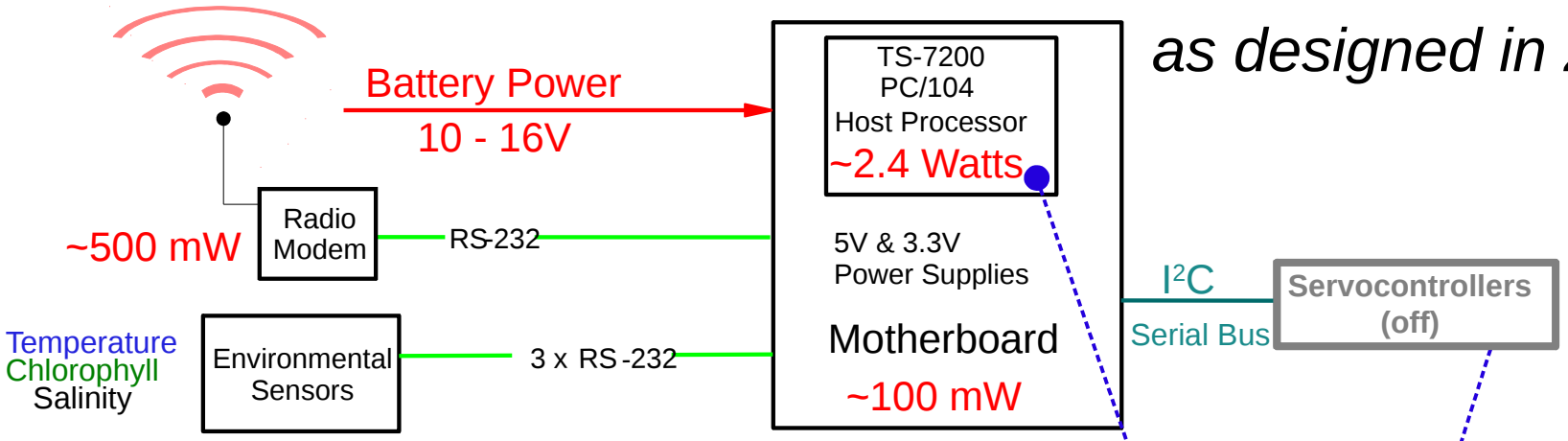
➔ More kB RAM would have been worth added mWs

Energy Required to actively Process Pucks

- 25 Watt / hrs to process each set of 4 pucks
  - For typical, 3 hour HAB species identification
- Deployment consists of 33 such puck sets
- 25 Watt / hrs / puck set * 33 puck sets = 825 Wh
  - To process all 132 pucks
- Battery has 6000 Wh capacity
- So, we have plenty of energy...
- Right?



Processor load while “Idle” limits deployment

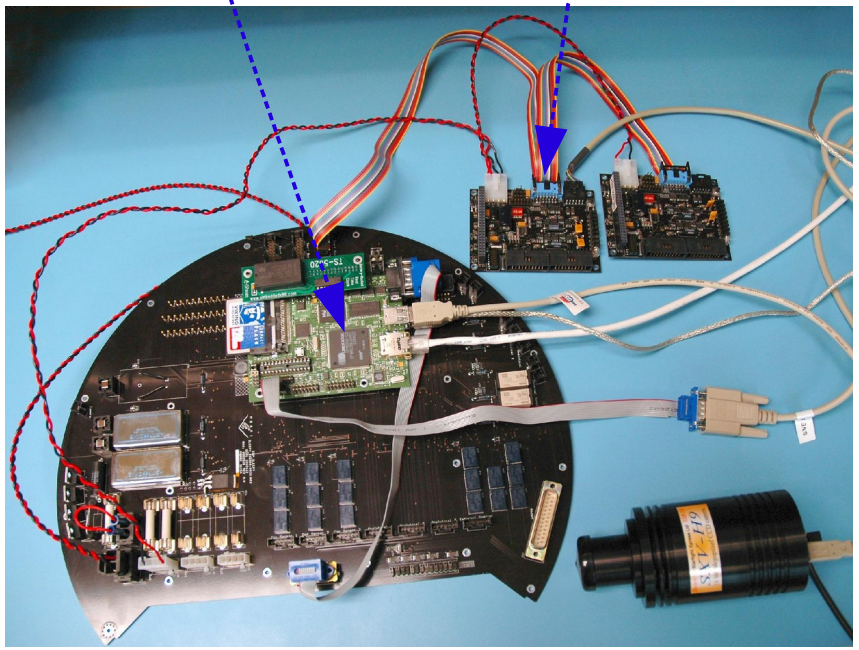


as designed in 2002

Pucks are precious:
Poll environmental sensors
for cues to fire off next assay

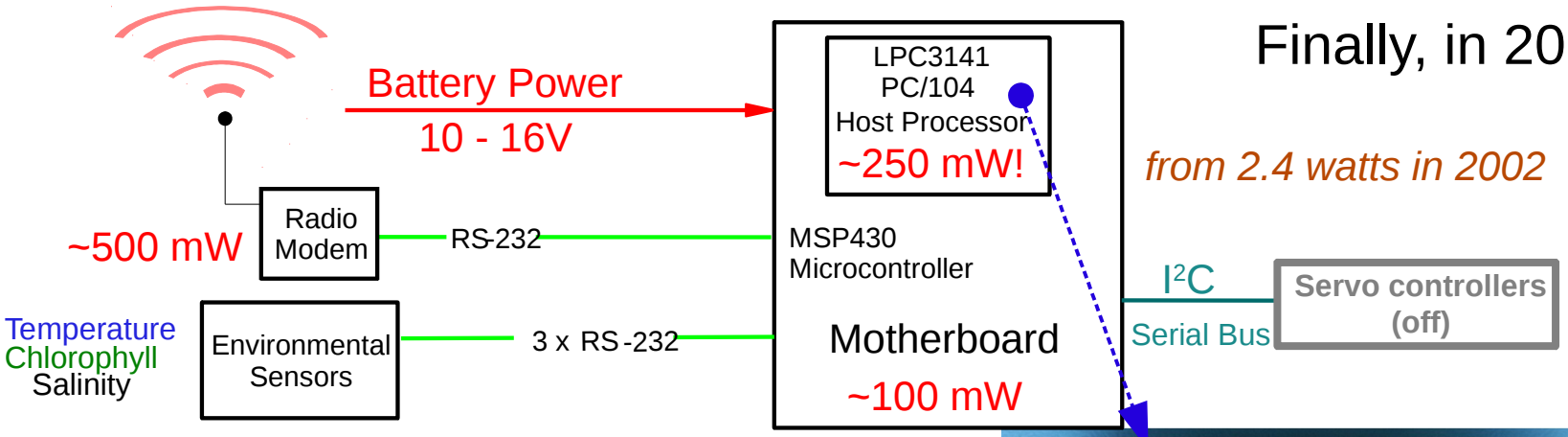
~3 Watt total load while “Idle”
Monitoring Environment
= 75 Wh/day
= 2250 Wh/month
5125 Wh depleted in only 68 days

Far short of 180 day goal :-(



Technologic Systems TS-7200 200Mhz ARM9
64MB RAM, 16MB NOR flash, 2.4 Kernel

Reduced Load with custom Linux Host



Finally, in 2014

from 2.4 watts in 2002

Reduced 3W total “idle” load to 1W

~1 Watt total load while “idle”
Monitoring Environment
= 25 Wh/day
= 750 Wh/month
5125 Wh depleted in 205 days !

Mission Accomplished?

Embedded Artists LPC3141 270Mhz ARM9
64MB RAM, 256MB NAND flash, 2.6 Kernel

WHOI Stretch Hose ESP Mooring

- Designed to survive Atlantic Ocean storms
  ESP ~22 meters deep (under waves)

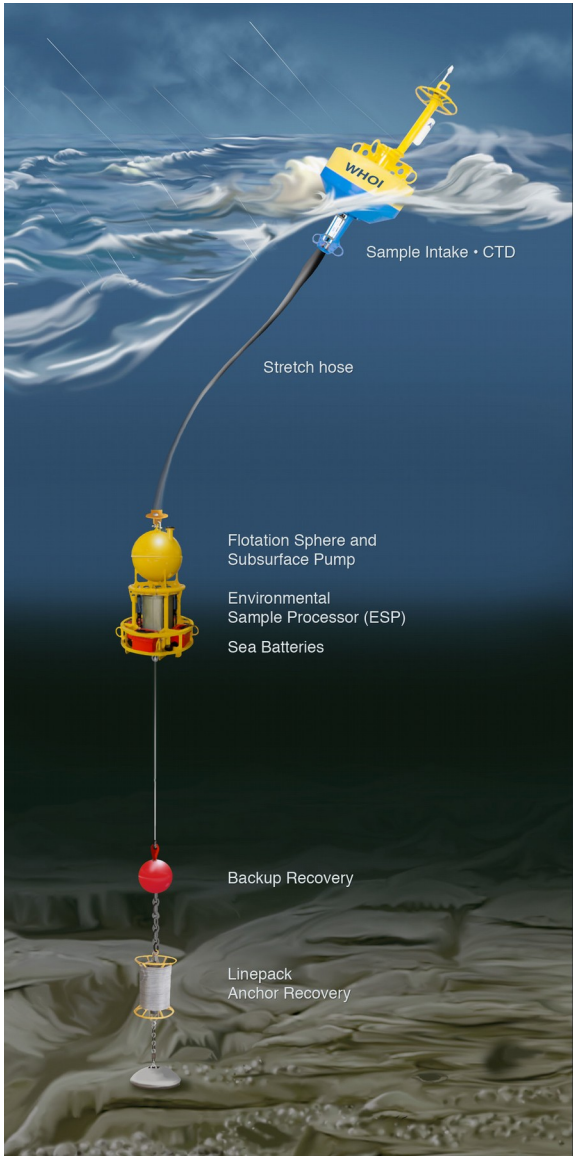
- Wires in stretch hose are >65 meters long
  No twisted pairs – will not pass Ethernet!
- DSL links radio in float with ESP below
  Uses Ethernet within float and ESP

- Idle Mode load increased to >8 W

- Max deployment duration <60 days
  Even with >3x battery capacity

- Retrofitting with new 250mW CPU board
  Does not change much

WHOI = Woods Hole Oceanographic Institution



High Speed Over Long Wires Saps Power

DSL

Symmetric Digital Subscriber Line:
- Pushes Mb/s over most any cable
- But, links typically use >4 watts

Ethernet:
- 100BaseT link uses 1 watt
- 10BaseT uses only 400mW

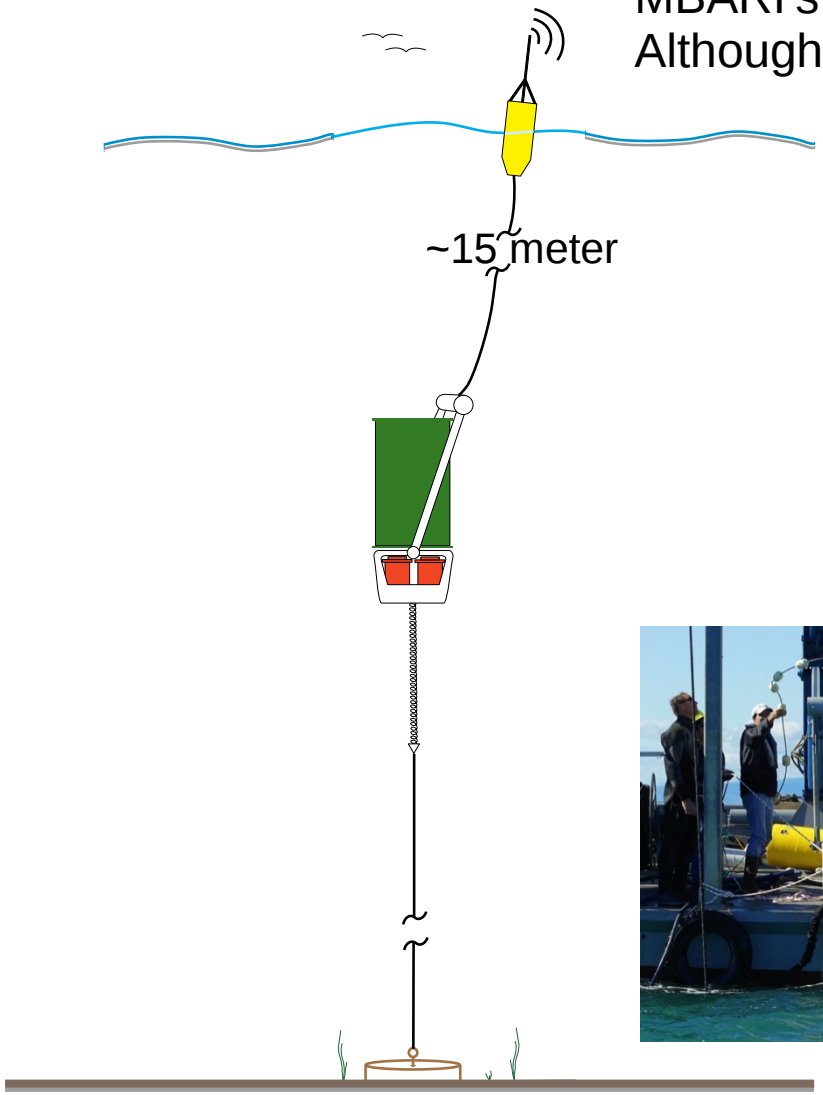
Old, slow tech saves power!

With today's low power Linux processors, such links blow the power budget

RS-232 cable length vs max speed

RS-232 works well beyond its recommended speed/length limit

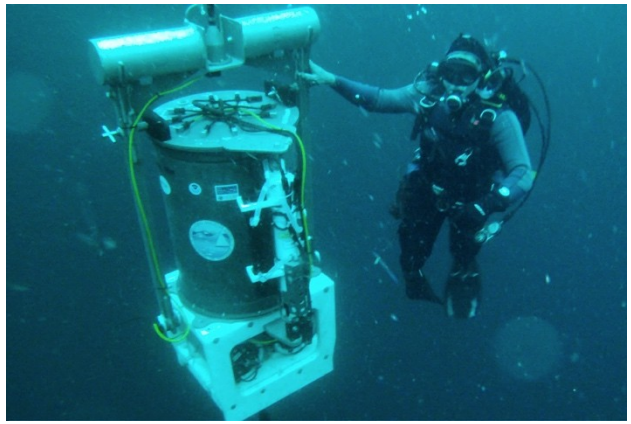
MBARI's ESP mooring runs 115 kBaud over 12m cable
Although RS-232 spec would suggest ~19.2kBaud limit



Much maligned but still used in oceanography

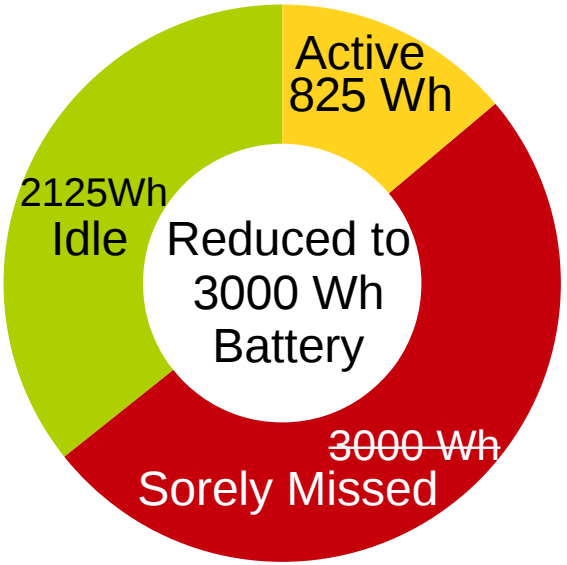
+ RS-232 is often lowest power option
+ Compatible with every processor
+ No (intrinsic) length limit
  300 baud can push through kms of wire

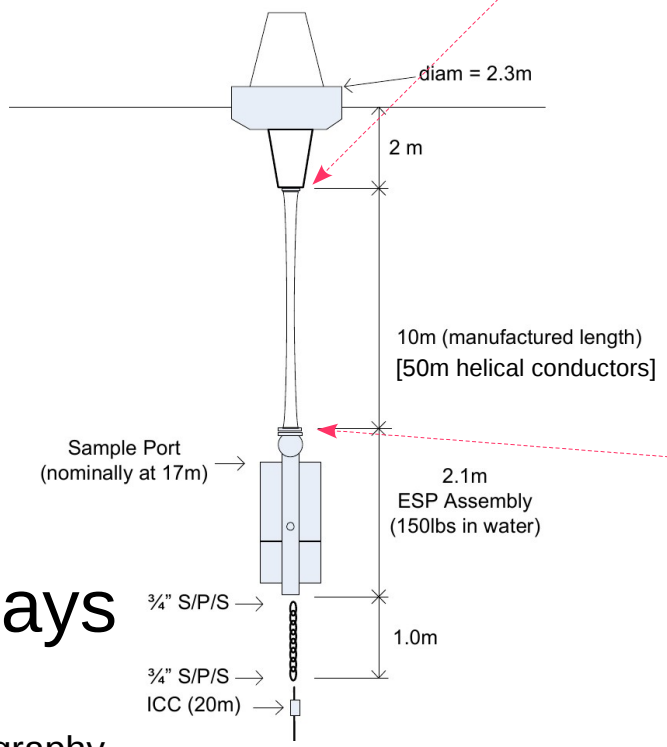
+ RS-422 can push higher rate on long cables
  - but requires twice as many conductors

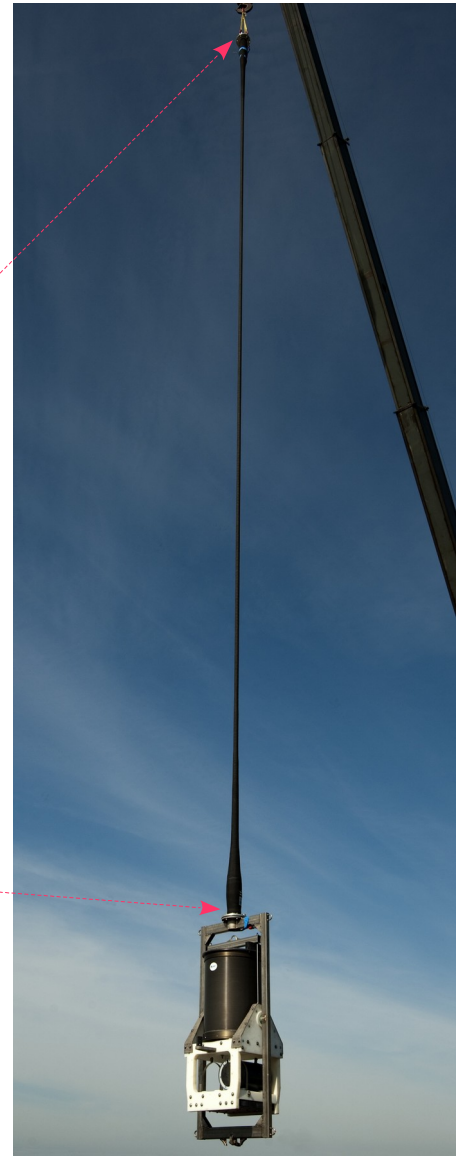


SCRIPPS Stretch Hose Mooring

- ESP hangs from 10m stretch hose
- RS-422 used for 65m link to float
- One battery removed to reduce mass
  - Capacity halved to 3000 Wh
- Need 6 month mission duration







- ➔ Depleted in just 85 days
- ➔ With 1W load

SCRIPPS = Scripps Institution of Oceanography

Quick Fixes We (briefly) Considered

Suspend-to-RAM?

- Lowers host CPU power by only 100mW
  - Reducing monitoring mode load to 0.85W
  - Increasing deployment by only 15 days

Suspend-to-Disk?

- Concerns about SD card
  - Slow write speed
  - Flash wear over 100s of hibernate cycles
- Hibernation not implemented in 2.6 ARM kernels

Rethinking Requirements

- If all activity is triggered only by time...
  - No need to monitor sensors
  - Host CPU could be powered off
    - Until switched on again by motherboard

- Even this yields only enough power for 140 days
  - Radio has become the power hog
  - If it must shutdown, how will unscheduled access be possible?

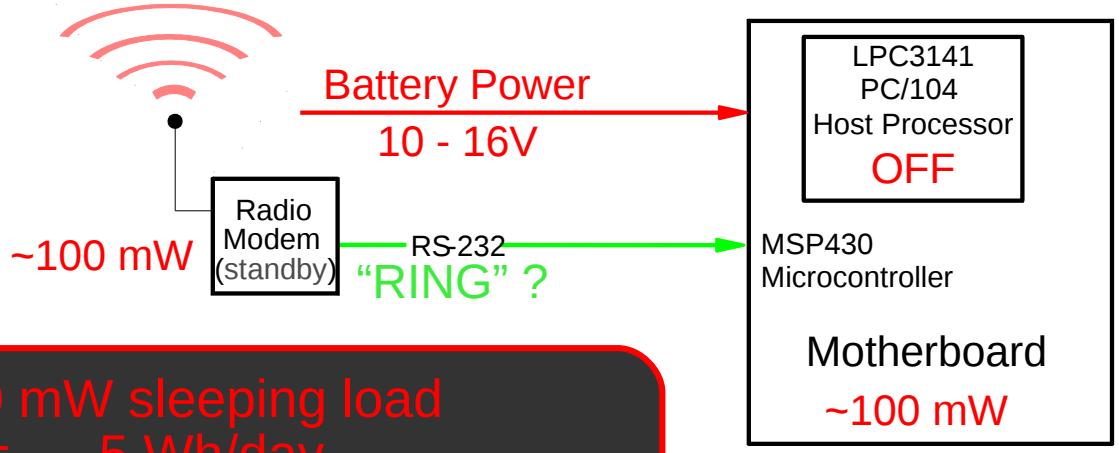
Deep sleep while allowing remote wakeup

Utilizing modem's “low-power standby” mode

- Drop the data connection
- Modem functions as a pager.
- Outputs
  “RING”

  when it detects an incoming phone call.
- Draw reduced from 500mW to 100mW

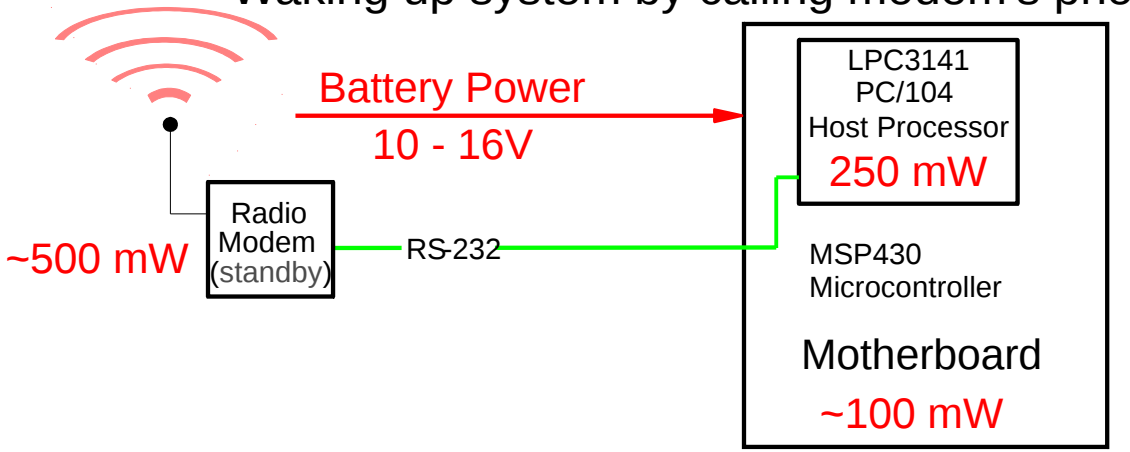
Year long deployments possible on 3kWh



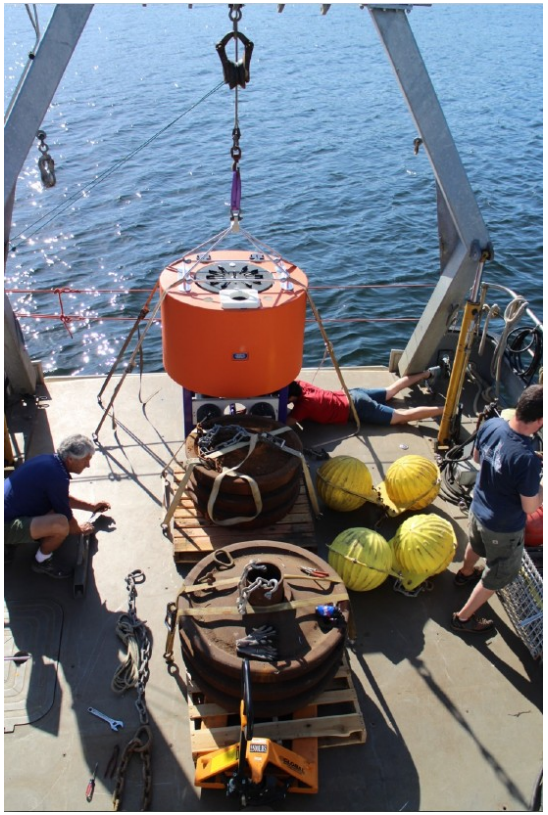
~200 mW sleeping load
= 5 Wh/day
= 150 Wh/month
2125 Wh depleted in 425 days !

Not monitoring sensors while asleep

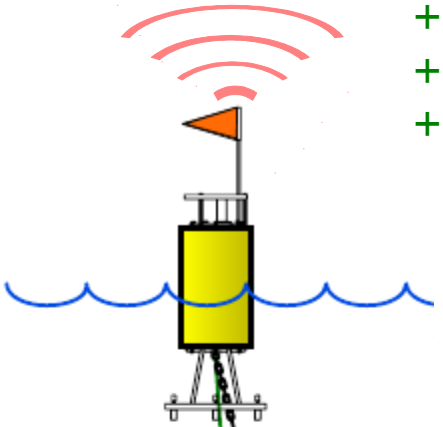
Waking up system by calling modem's phone #



University of Washington's ESP Mooring



+ Suitable for open ocean
+ Relatively inexpensive
+ No stretch hose



40m Cat 5 cable to surface is too long for RS-232

~650kg

Foam Float Collar
(around ESP core)

Large Float collar protects ESP
and
Eliminates need for rotating bale

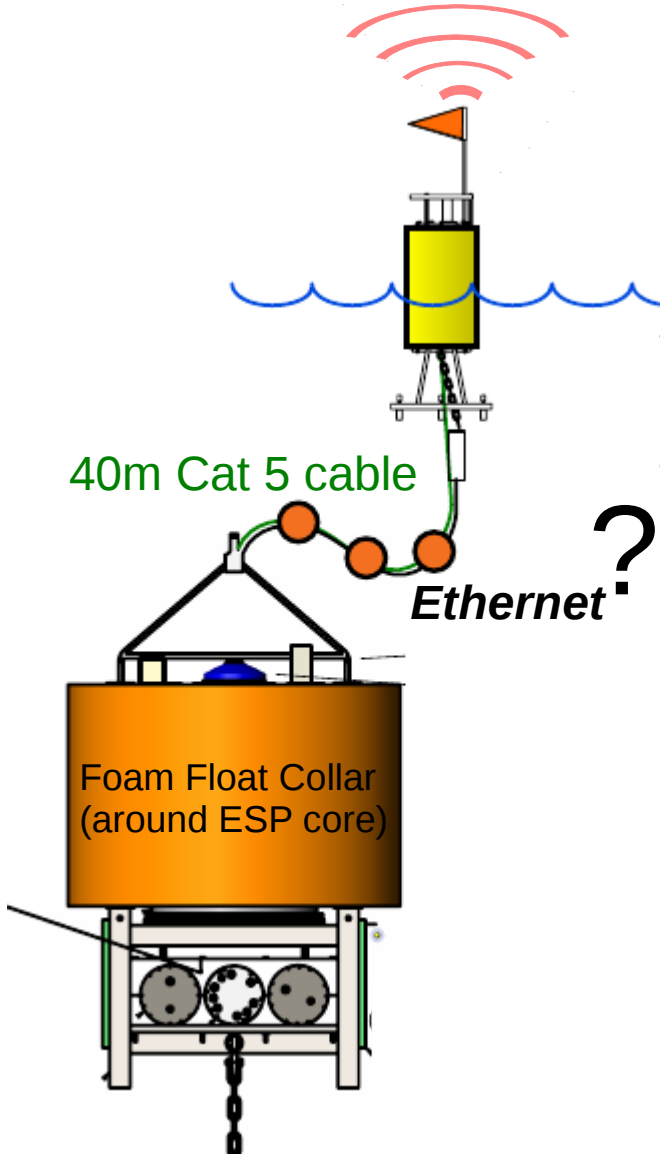
400 Alkaline 'D' Cells
6.1kWh

Taut Line to 1 ton Anchor

Replace RS-232 with Ethernet?

+ Directly drives 40m Cat 5 cable
+ >100 times faster than RS-232 to modem
+ Unlimited networking potential

- Each device is a computer itself
- Adds minimum of 1W per device
- No “class drivers”

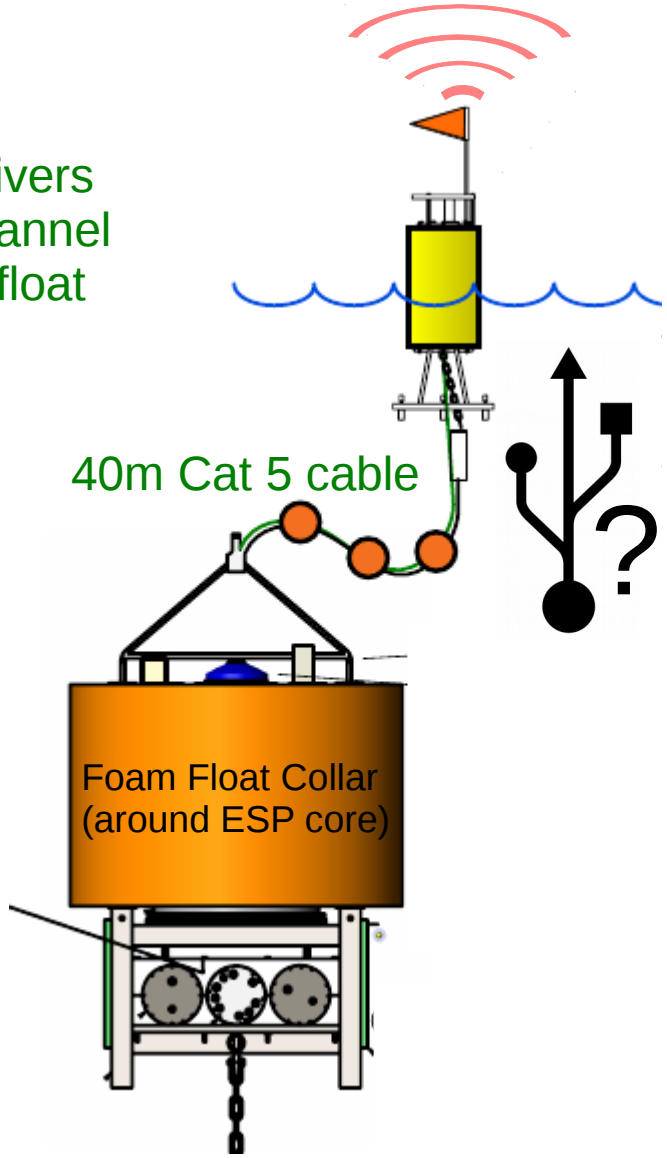


Replace RS-232 with USB?

+ >100 times faster than RS-232 to modem
+ Linux kernel includes many USB class drivers
+ Hubs multiplex 100+ devices per USB channel
+ Directly support additional devices in the float
  Environmental Sensors, WiFi, etc.

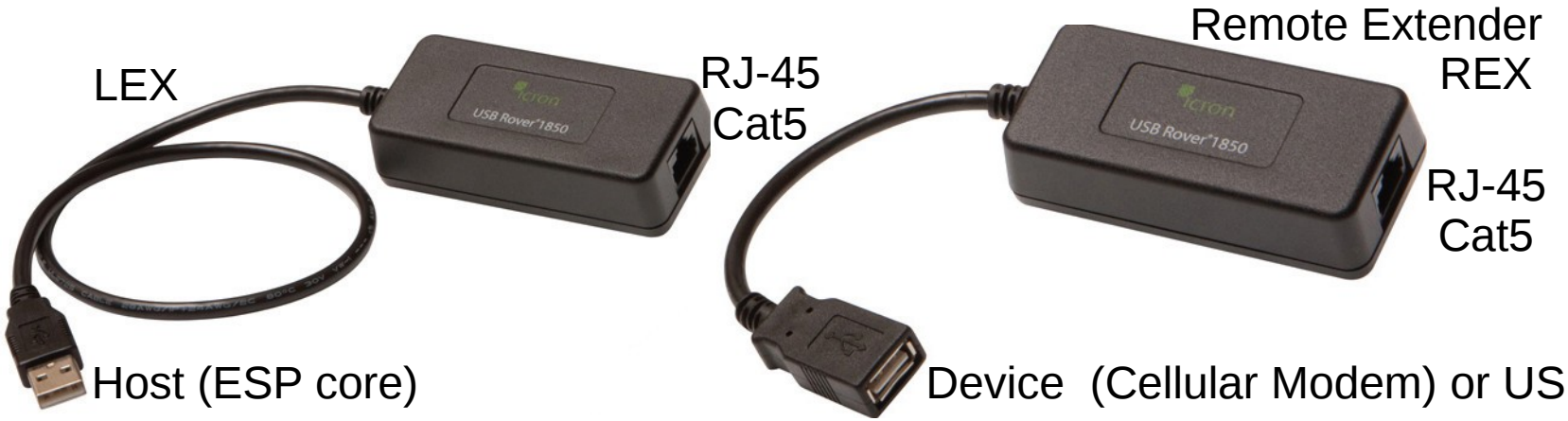
- Adds about 30mW per device
- Hubs draw 150mW each!
- Segment length limited to 5 meters

➔ But, we need to span 40 meters.



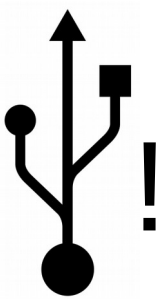
USB on Cat5 cable

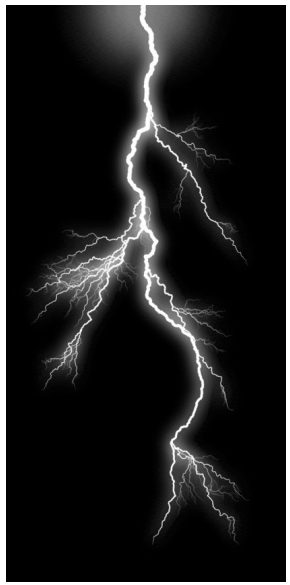
Many Cat5 USB extenders available...
Icron 1850 works reliably over 50 meters of cable:



- Full Speed (12Mb/s) and Low Speed (1.5Mb/s) only
- Supports remote hubs, transparent to software
- 12Mb/s link burns 500mW
- *Newer designs support 480Mb/s, burn >2W*

→ Precludes low power sleep in current ESP design
→ Would require a dedicated RING signal from modem





Note: Many other vendors rebrand Icron USB extenders

USB 2.0 Power Management Theory & Practice

- Most devices ignore requests to suspend
  - Suspended devices still draw ~30 mWs
- Most hubs do not support powering down ports
- Laptop users simply unplug unused USB devices
  - ➔ **Embedded systems can do the same**
- Power USB devices via GPIO controlled switches
  - USB stack sees usual dev disconnect / connect
  - No need to splice high speed data lines

Energy Harvesting

Need only 50 Wh/day ~= 2W continuous

- Solar requires least maintenance
- >3 hrs sunlight/day in temperate latitudes
  - Need panel w/peak rating of ~25W
  - 25W panel area ~= 0.25 square meters
- Might blow over existing small surface floats
  - Tipping > 30 degrees interferes with radio
- Rechargeable battery & new float design required
  - But very doable and worth investigating...

The Road to > 6 months on 6 kWh

- High Energy (Alkaline) batteries
- Custom Low Power Electronics
  - Servo controllers optimized for small motors
  - Lower power ARM9 Linux Host
- Avoiding modern high speed serial links
  - Using RS-232 instead of Ethernet and DSL

The Road to > 6 months on ***3 kWh***

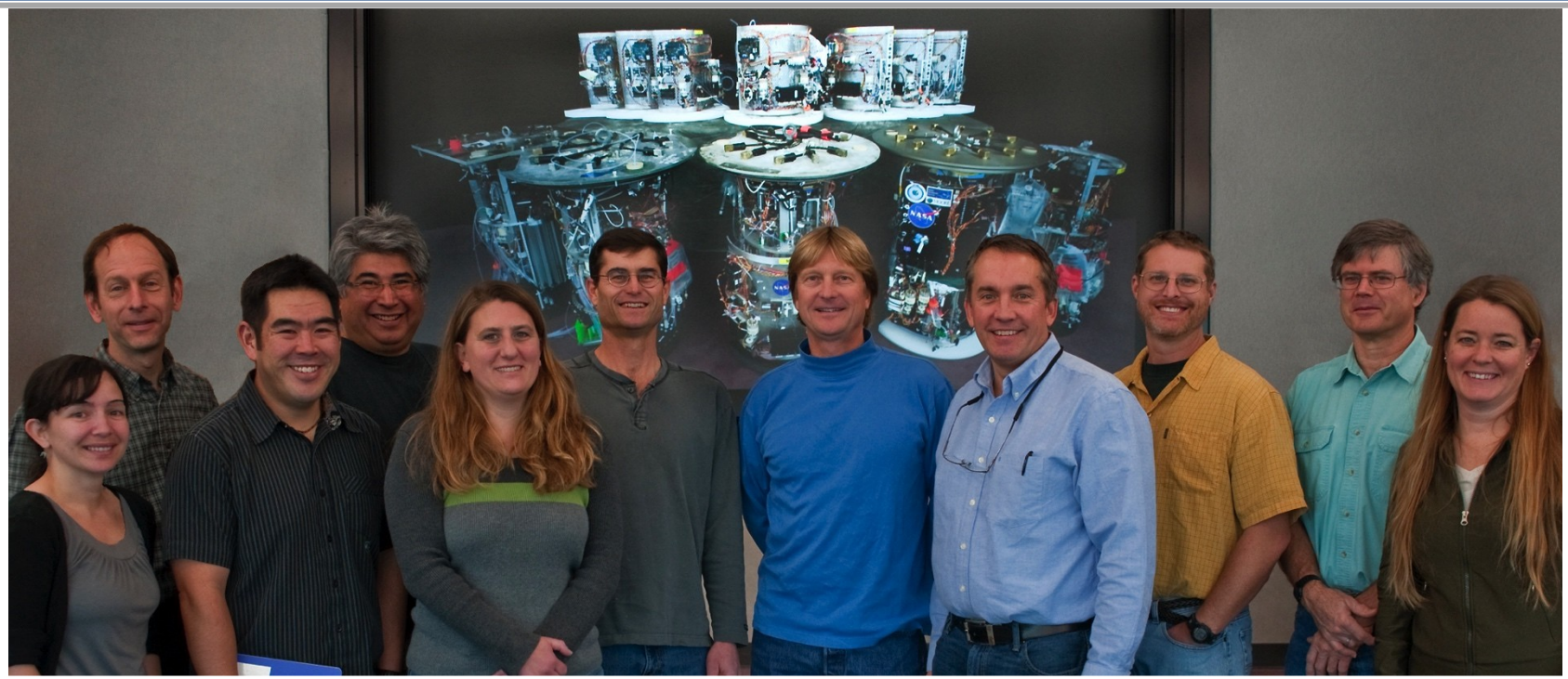
All the previous measures, plus...

- Relaxing requirements for environmental monitoring
  - Allowing complete shutdown of Linux host
- Radio comms power management
  - Exploit modem's low-power standby mode

In Future:

- Indefinite Environmental Monitoring...
  - with solar panels on the surface float!

Acknowledgements



the David & Lucile Packard FOUNDATION

MBARI Monterey Bay Aquarium Research Institute

Gordon and Betty MOORE FOUNDATION

NSF

SCCWRP Established 1969

NASA

C-MORE